The First Planets

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We explore the conditions under which, according to the two leading theories of planet formation, the first planets formed in the early universe. In the context of the core accretion model for planet formation, we estimate that the minimum abundance of heavy elements required for planet formation is $[Fe/H]_{crit} \sim -1.5 + \log(r/1\ \mathrm{AU})$, where r is the distance between the planet and its host star, an astronomical unit (AU) is the distance between the Earth and the Sun, and here the iron abundance relative to that of the Sun [Fe/H] is a proxy for the abundance of heavy elements. This minimum value implies that the first Earth-like planets likely formed around stars with heavy element abundances at least one-tenth that of the Sun. We find, however, that the first gas giant planets may have formed via gravitational instability in circumstellar disks, instead of via core accretion, although in this case they must have formed within a few AU of their host stars. We show that the available observational data are consistent with these predictions.

Following the formation of the first stars and galaxies, the formation of the first planets marks a milestone in the increasing complexity of the cosmos. When and where the first planets form depends in large part on the mechanism by which they form–there are two main models for how planet formation takes place. In the core accretion model, dust grains coagulate and settle into the mid-plane of a circumstellar disk, where they merge to form planetesimals and eventually the cores of planets. This is the prevailing model for how rocky, terrestrial planets take shape, although if the cores that form accrete large amounts of gas then gas giant planets may form as well [1]. In the gravitational instability model, a circumstellar disk grows to the point that it fragments into planets under its own gravity–it is thought that this model can explain the formation of some gas giant planets, although it cannot account for terrestrial planets [2].

When the abundance of heavy elements is very low in a circumstellar disk, as is the case in the early universe when only the earliest supernovae have chemically enriched the gas, there are two factors that work against planet formation in the core accretion model. First, it takes much longer for dust grains, of which there is a low abundance, to collide with one another, grow, and settle into the mid-plane of the circumstellar disk [3]. Second, due to the lower opacity to ultraviolet (UV) and X-ray photons emitted from the host star, the circumstellar disk is photoevaporated away much more quickly than its more chemically enriched counterparts, and once the disk is destroyed planet formation can no longer take place [4]. Therefore, there is a competition between these two time scales, and it is only above some minimum, or "critical," heavy element abundance that there is time for dust grains to coagulate and form planetesimals before the circumstellar disk is destroyed by radiation from the host star [5]. Figure 1 shows this critical heavy element abundance, expressed as the iron abundance relative to that of the Sun [Fe/H], as a function of distance r from the host star. Below the critical abundance planet formation is not possible and so this is termed the "forbidden zone" for planet formation via core accretion. The data on several hundred observed planets [6] are also shown, all of which lie safely outside the forbidden zone, indicating that they may have formed via core accretion.

In the other main model of planet formation, gravitational instability, it is possible that gas giant planets could form in circumstellar disks with heavy element abundances below the critical value for the core accretion model. Indeed, the recently reported detection of a gas giant planet on a wide orbit around a heavy element-depleted star provides some indication that this may take place [7]. While planet formation via graviational instability is not likely to occur in the disks surrounding the first stars, as they are much too hot to be subject to gravitational fragmentation at the small scale of planets, slightly chemically enriched circumstellar disks could cool sufficiently for this mode of planet formation to function [8]. In the early universe, however, there is a fundamental lower limit to the temperature to which disks can cool radiatively that is set by the cosmic microwave background (CMB) radiation. Because the temperature of a circumstellar disk cannot go below the temperature of the CMB, planets could only form via gravitational fragmentation relatively close to their host stars–outside some maximum radius there is a second forbidden zone within which planet formation via gravitational instability is not possible. Because the temperature floor set by the CMB is higher

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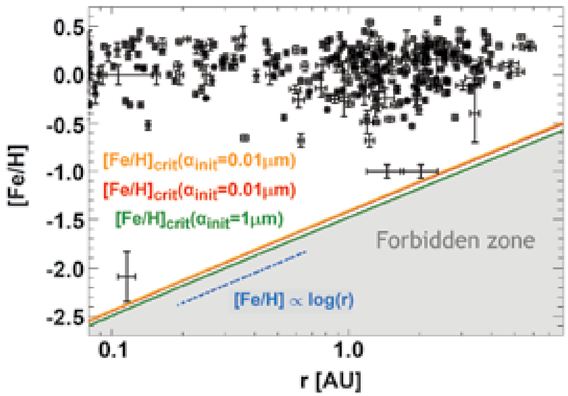

Fig. 1. The critical metallicity for planet formation, expressed as the iron abundance relative to that of the Sun [Fe/H], as a function of distance r from the host star. The three colored lines correspond to different initial dust grain sizes, as labeled. The curves shown here are well approximated by $[Fe/H]_{crit} \sim -1.5 + \log(r/1\ AU)$, where an AU is the distance between the Earth and the Sun. The black crosses show the iron abundance [Fe/H] of observed planet-hosting stars plotted against the semi-major axes of the planets' orbits. Planetary systems that lie below this line, in the forbidden zone shown in gray, are unlikely to have formed through core accretion, at least not at their present locations.

at earlier cosmic times, this maximum radius is smaller at earlier epochs, as shown in Fig. 2. Also shown are the data on gas giant planets orbiting stars with low heavy element abundances. The vast majority of the planets lie well below the forbidden zone, although there are a few very old planets and planets on very wide orbits that lie outside of it. Thus, most of the planets shown could have formed via gravitational instability unhindered by the constraints placed by the CMB temperature floor–those few in the forbidden zone, however, may have formed via core accretion instead.

In particular, the single heavy element-depleted gas giant planet recently reported to lie in the forbidden zone for core accretion [7] lies well outside of the forbidden zone for gravitational instability. This suggests that the first planets may have been gas giants formed via gravitational instability, although the first terrestrial planets must have instead formed via core accretion. In turn, the first terrestrial planets as large as our Earth, which may have hosted the first life in the cosmos, are expected to have formed via core accretion only once the heavy element abundance of circumstellar disks was at least a tenth of that of the Sun [5].

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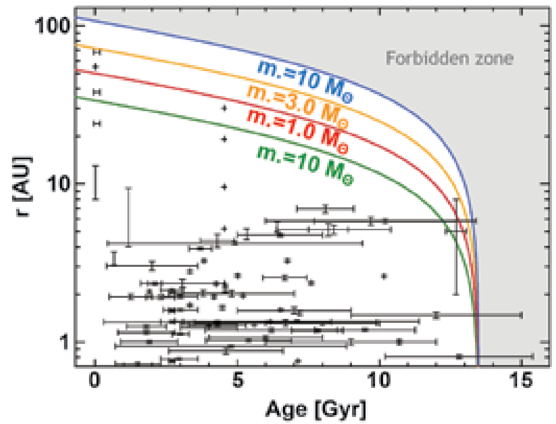

Fig. 2. The semi-major axes (vertical axis) of the orbits, and host stellar age (horizontal axis), of observed planets are shown as black crosses. The colored lines show the maximum possible distance r_{max} at which planets can form from their host stars via gravitational instability as a function of their present age, for four different host stellar masses, as labeled. Beyond this maximum distance, it is predicted that planet formation is not possible via gravitational instability due to the temperature floor set by the CMB, and so this region of the plot is termed the forbidden zone for planet formation via gravitational instability.

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